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Synergies Between NASA's Hyperspectral Aquatic Missions PACE, GLIMR, and SBG: Opportunities for New Science and Applications

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Key Points:

- Upcoming ocean color satellites offer new opportunities to study processes across the continuum of inland-coastal-oceanic environments
- Common working groups, algorithms, shared field and simulated data sets, calibration, validation, and atmospheric correction capabilities
- Combining unique spatial and temporal capabilities of each mission allows for new interdisciplinary applications

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Abstract Within the next decade, NASA plans to launch three new missions with imaging spectrometers for aquatic science and applications: Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) in 2024, Geostationary Littoral Imaging Radiometer (GLIMR) in 2026, and Surface Biology and Geology (SBG) in 2028. Taken together, these missions will evaluate long-term trends in phytoplankton biomass linked to climate change, and provide new spectral capabilities to assess aquatic biogeochemistry, biophysics, and habitats. Hyperspectral measurements of ocean color, paired with advanced retrieval algorithms, can provide new information on phytoplankton community composition and water quality. We compare the mission architecture and sensor characteristics to identify the synergistic opportunities to merge algorithms, field data, and calibration and validation techniques. Each mission has unique temporal and spatial characteristics to monitor the aquatic transitions from watershed to open ocean ecosystems. SBG provides observations at high spatial scales to monitor emergent, floating, submerged, and benthic habitats from inland to coastal waters. With global daily coverage, PACE can track the fate of material as it meanders offshore and provides an enhanced context for phytoplankton diversity and global biogeochemical cycling. GLIMR is optimized to resolve temporal processes that give rise to aquatic rates and fluxes including phytoplankton growth rates, physiology, and episodic events such as storms. Applications with high spectral, spatial, and temporal resolution from these NASA missions include assessing carbon dynamics and biogeochemical cycling across the land-ocean continuum, harmful algal blooms, and oil spills.

Plain Language Summary NASA plans to launch three new missions for monitoring aquatic ecosystems from space: PACE in 2024, Geostationary Littoral Imaging Radiometer in 2026, and SBG in 2028. Each mission monitors unique space and time scales from inland water quality to coastal seagrass habitats to upwelling zones supporting rich phytoplankton blooms. Having many more wavebands than historic sensors, these missions will allow us for the first time to monitor phytoplankton diversity from space and how different communities of these microscopic photosynthetic organisms produce oxygen, consume carbon dioxide, and serve as the base of the aquatic foodweb. Merging data from these three missions will allow us to better link processes across the continuum from inland lakes and rivers to the major ocean basins and assess hazards impacting coastal communities.

1. Introduction

The next generation of ocean color remote sensing is coming! For 25 years, satellite assets have been continuously quantifying the photosynthetic pigment chlorophyll *a*, a proxy measure of phytoplankton biomass and carbon uptake (Gregg & Rousseaux, 2019; McClain et al., 2022). These robust satellite retrievals from ocean

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color instruments (OCIs) have leapt oceanography forward in gaining new knowledge about ecology, geophysical dynamics, ocean biogeochemistry, and air-sea interaction. With this long-term satellite record, we also monitor and quantify the very real and rapid changes occurring to aquatic ecosystems across the globe including eutrophication of inland and coastal waters and responses to atmospheric greenhouse gases (Cael et al., 2023; Hammond et al., 2020). Maintaining the quality of this long-term record has been a herculean task involving teams of engineers and scientists pouring over imagery and data from moorings maintained in the middle of the ocean, countless rounds of careful reprocessing, newly tuned models, and careful trend detection (Franz et al., 2005; McClain et al., 2022). It might be tempting to rest on our laurels and relegate aquatic remote sensing to the operational realm with a badge that reads "job well done." But the hidden truth is that many challenges for aquatic remote sensing remain, and there is still much more to be done (Bisson et al., 2021; Dierssen, 2010). Pulling information out of the very dark color of the water from the bright noise of the atmosphere and surface-reflections of direct and diffuse sunlight can still elude our best models (Frouin et al., 2019). The complexities of coastal and inland waters require more information than we can get with sensors that measure light at only a few bands (Dekker et al., 2018), and frankly, chlorophyll *a* is not an adequate metric to describe the diversity of changes to water color and biodiversity of aquatic ecosystems (Bracher et al., 2017; Westberry et al., 2016). As noted by Sosik et al. (2003), "our knowledge of the factors regulating phytoplankton populations at and below the mesoscale remains limited by inadequate sampling and our inability to measure the species composition, size distribution, and growth rate of the phytoplankton community." The next generation of NASA aquatic missions are designed to open the door and fuel novel research to allow us to look at the ocean with innovative sensors, enabling a wave of new algorithms and products, which open our imagination to what we cannot "see" with our own eyes.

As early as 1847, J.D. Hooker in the "Botany of the Antarctic Voyage," eloquently describes the abundance of diatoms and noted how they impart "ochre" or yellow-orange color to neighboring ice:

"The waters and the ice of the South Polar Ocean were alike found to abound with microscopic vegetables belonging to the order Diatomaceæ. Though much too small to be discernible by the naked eye, they occurred in such countless myriads as to stain the berg and the pack ice wherever they were washed by the swell of the sea; and, when enclosed in the congealing surface of the water, they imparted to the brash and pancake ice a pale ochreous color." Hooker, J.D.

We now know that diatoms are ubiquitous across the global ocean, but measurements of the "ochreous color" or yellow-orange part of the visible spectrum (590–640 nm) have been missing from the historic set of wavebands operationally used for ocean color remote sensing (Figure 1), although a band at 620 nm has been included in the European Space Agency's MERIS and OLCI sensors. A large gap of nearly 100 nm, covering one third of the visible spectrum of light, is the norm for the operational fleet of NASA and NOAA ocean color sensors like VIIRS. This large gap is about to close with the advent of three new NASA missions slated to probe aquatic ecosystems: Plankton, Aerosol, Cloud, ocean Ecosystem (PACE; http://pace.gsfc.nasa.gov) (Werdell et al., 2019), Surface Biology and Geology (SBG; http://sbg.jpl.nasa.gov) (Cawse-Nicholson et al., 2021), and the Geostationary Littoral Imaging Radiometer (GLIMR; http://eos.unh.edu/glimr) (Salisbury, 2022). With this new investment in satellite ocean color, NASA is reenvisioning missions designed and built to explore aquatic biology and biogeochemistry. This is the result of both investments in new sensors and data technology that will provide new insight across the vast aquascape covering two thirds of the planet.

While definitions vary, we hereafter refer to "hyperspectral" remote sensing as imaging spectroscopy that provides a continuous measurement across the visible spectrum with bands that are separated by less than 30 nm (Dierssen et al., 2021). While some sensors evolved from lessons learned from heritage satellite missions (Meister et al., 2022), others came from a small legacy of prototype airborne and satellite hyperspectral sensors, most of them designed for the higher reflectance of terrestrial applications and not optimized to sense the generally "dark" clear waters of the oceanic gyres or crystal clear mountain lakes (Giardino et al., 2019). New sensor technology developed over the last decade has improved sampling over a large dynamic range from dark oceanic waters to bright shallow coral reef ecosystems to bright atmospheric aerosols and clouds (Bender et al., 2018; Mouroulis et al., 2008). As highlighted in Figure 2, prototype satellites such as Hyperion and HICO have provided hyperspectral data in the last two decades. However, all present and historic hyperspectral missions are regional in scope and only collect imagery from specific targeted locations. NASA's OCI, the primary of three instruments on the PACE observatory, and SBG are the first hyperspectral sensors to be global in scope collecting data routinely along each swath. GLIMR is the first hyperspectral geostationary satellite that will collect multiple images daily across a defined region of the globe.

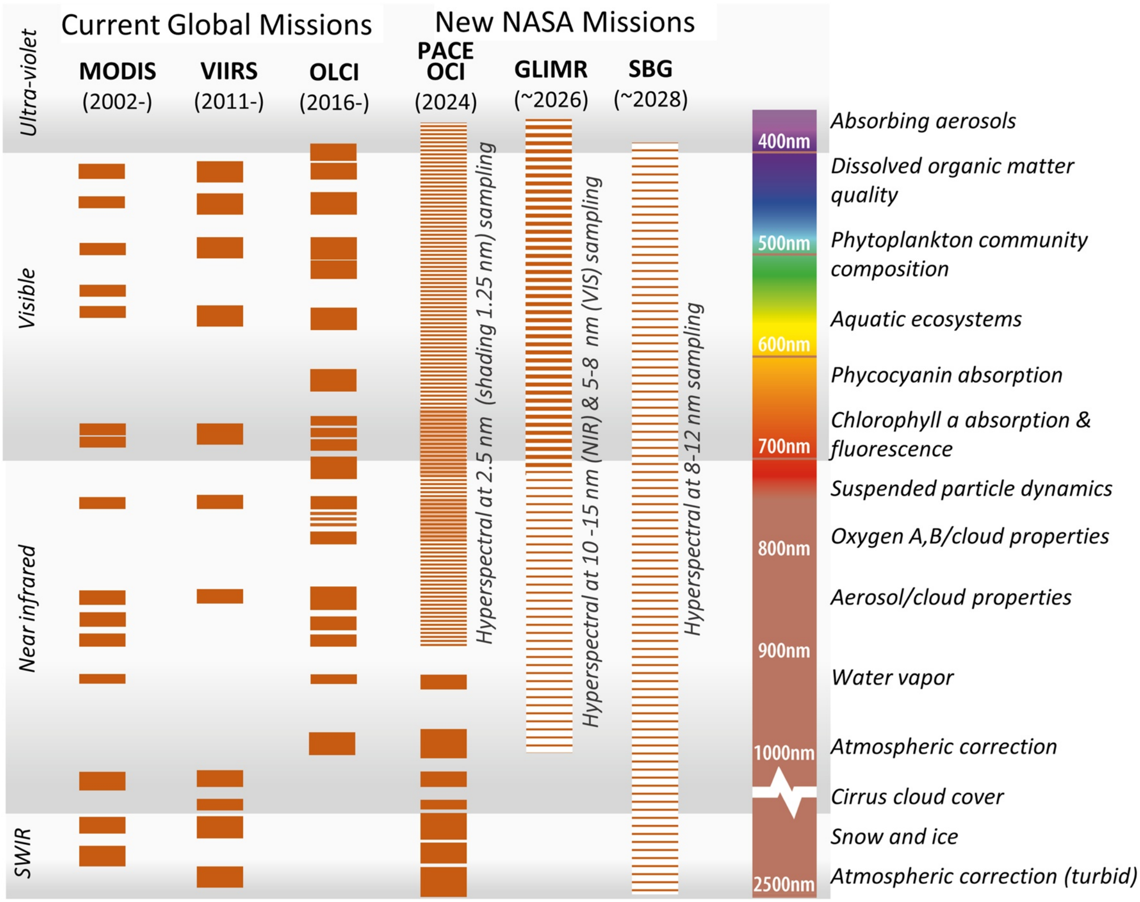

Figure 1. Comparison of the spectral sampling of the three new NASA hyperspectral missions (Plankton, Aerosol, Cloud, ocean Ecosystem [PACE], Geostationary Littoral Imaging Radiometer [GLIMR], and Surface Biology and Geology [SBG]) compared to the multi-channel capabilities of global ocean color sensors. Adapted from Schollaert Uz et al., 2019.

2. Mission Characteristics

The three missions provide an unprecedented opportunity for observations of inland, coastal, and open ocean aquatic environments because each mission covers a different range of spatial and temporal scales. Mission architecture and orbital characteristics include both Low Earth Orbit (LEO) orbits for PACE and SBG and the Geostationary (GEO) orbits planned for GLIMR (Table 1). The observations from the missions will cover the ultraviolet (UV), visible (VIS), near infrared (NIR), short-wave infrared (SWIR), and thermal infrared (TIR) portions of the spectrum. The characteristics provided for SBG and GLIMR are current objectives; these missions are in the early phases of development and some values may change (Table 2). If the missions overlap temporally, there is strength in fusing algorithms and data for capturing and following events (e.g., harmful algal blooms, riverine plumes, oil spills, glacial melt and calvings, and water quality). The orbital characteristics of each mission may also provide an ability to resolve different aquatic processes from large-scale daily sampling across the oceans with PACE, to investigating submesoscale features of nearshore aquatic ecosystems at high spatial resolution with SBG, to exploring diurnal variability of the Gulf of Mexico with GLIMR (Figure 3). Following its long history of providing publicly available data, NASA will make all data and imagery open access and findable, accessible, interoperable, and reusable (FAIR) (ESDS, 2023).

2.1. PACE Mission

The PACE mission, scheduled to launch in early 2024, will host the OCI, which consists of two overlapping spectrometers operating in whiskbroom mode spanning the ultraviolet-to-visible and visible-to-near-infrared spectral regions at 5 nm resolution, as well as seven additional discrete detectors to collect measurements at heritage near

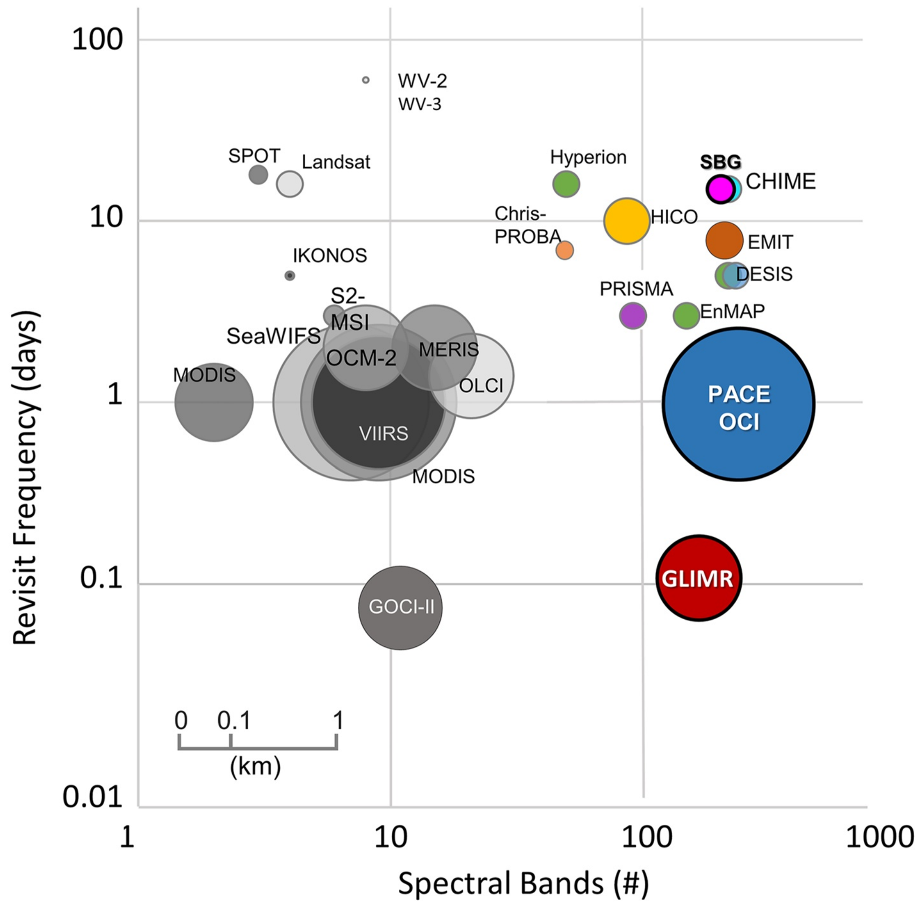

Figure 2. Architecture of various international missions showing the tradeoff between number of spectral bands, revisit frequency, and the spatial footprint (approximated as the size of circle). Gray represents multi-spectral missions and colors represent the hyperspectral missions. The upcoming NASA missions in bold include PACE and SBG, the first to be global in scope, and Geostationary Littoral Imaging Radiometer, the first hyperspectral geostationary sensor. Modified from Dierssen et al. (2021).

infrared and shortwave infrared wavelengths useful for monitoring the atmosphere and turbid waters. Similar to the heritage Sea-viewing Wide Field-of-view Sensor (SeaWiFS) satellite, the sensor will be tilted along-track at ±20° fore and aft of the sun to minimize sun glint. The two spectrometers will provide spectral sampling in 2.5 nm steps across the full swath and higher resolution 1.25 nm step across the chlorophyll fluorescence and oxygen A,B absorption regions. Unique to this sensor, the signal-to-noise will also be enhanced with a lower gain setting in the chlorophyll *a* absorption/fluorescence and red edge regions of the spectrum. The entire globe will be imaged each day for atmospheric retrievals and effectively every 2 days for ocean color given geometric constraints applied to atmospheric correction, with a nominal pixel size of 1.2 km^2. The PACE payload also includes two multi-angle polarimeters to measure the polarization state of the reflected light, namely the Hyper Angular Rainbow Polarimeter (HARP2) built by the University of Maryland Baltimore County and the Spectropolarimeter for Planetary Exploration (SPEXone) contributed by a consortium of organizations in the Netherlands. Together, these sensors will provide insights into the functioning and interactions of atmospheric aerosols, clouds, and ocean biology and are poised to make significant breakthroughs on phytoplankton dynamics (Cetinić et al., 2023) and ocean-atmosphere exchange (Remer et al., 2019).

2.2. GLIMR Mission

The GLIMR mission is scheduled to launch in the 2026–2027 timeframe. It will offer high fidelity, high-frequency radiometric measurements of ocean color from a geostationary orbit while targeting major portions of the Gulf of Mexico six times per day, and other coastal and ocean waters of North and South America (as well as calibration

Table 1
Orbital Characteristics of the NASA Missions

Mission comparison:	PACE OCI[a]	GLIMR	SBG
Architecture description	One satellite with overlapping imaging UV-VIS[1] and VNIR spectrometers plus 7 discrete NIR-SWIR bands Whiskbroom[b]	One satellite with an imaging UV- NIR spectrometer Pushbroom[b]	Two satellites; one with an imaging VSWIR spectrometer and another with a TIR sensor and multispectral VNIR imager Pushbroom
Orbit type	Ascending sun-synchronous LEO LTAN 1300	GEO, 98°W optimal	Descending sun-synchronous LEO LTDN between 1030 and 1130 for VIS-SWIR. Ascending sun-synchronous LEO LTDN 1230 ± 5 min for TIR/VNIR
Events targeting[c]	N/A, Global with a 1–2 days revisit cycle	Yes, Regional	No, Global with 16 and 3 days revisit cycles for VSWIR and TIR, respectively
Tilt	Dynamic along-track tilt at the sub-solar point (±20° fore and aft)	N/A	Fixed across-track tilt of ~5° from nadir anti-sun direction VSWIR

[a]Abbreviations: UV = ultraviolet; VIS or V = visible; NIR = near infrared; SWIR = short wave infrared; TIR = thermal infrared; LEO = Low earth orbit; GEO=Geostationary orbit; LTAN = Local Time of the Ascending Node; LTDN = Local Time of the Descending Node. [b]Whiskbroom—light is reflected into a single detector which collects data one pixel at a time as the detector rotates to scan across track as the spacecraft moves along track. Pushbroom—light is reflected into a line of sensors arranged perpendicular to the flight direction of the spacecraft. [c]"Events targeting" means that the sensor view angle can be changed to target specific episodic events or other monitoring priorities.

sites) at least twice per day. The Hyperspectral Imager aboard GLIMR will sample continuously from 340 to 1,040 nm, with 1–15 nm spectral resolution (<10 nm in the visible range) at a proposed ground sample distance of nominally 300 m at nadir. Using a two-axis gimbal to target specific locations at higher temporal frequencies, GLIMR will offer an unprecedented opportunity to study ocean processes at the combined, synergistic scales required to observe the dynamic ecological, biogeochemical, and physical processes typical of coastal and ocean waters. GLIMR will be equipped with a configurable scheduling capability, enabling a unique capacity to adaptively sample specific areas of interest in response to special events, such as oil spills, harmful algal blooms, or fluvial outflow events.

2.3. SBG Mission

SBG will include two platforms in low-Earth orbits that are both Sun-synchronous and polar crossing. One satellite targeted for launch in 2028 will carry an imaging spectrometer covering wavelengths from ~0.4 to 2.5 μm (VSWIR) with 10 nm continuous spectral sampling. This satellite will be in a descending morning orbit similar to the Landsat series and offer consistent Sun-viewing geometry and a 16-day equatorial revisit time. Based on a Landsat study, the mission currently has a requirement for an across-track, westward tilt in the range of 3–5° to minimize glint. However, the equatorial crossing time may be moved closer to 11:30a.m., a proposed across-track tilt of ≥5° may be considered. Like Landsat, the spectrometer will observe a 185-km wide swath with a ground sampling distance at nadir of approximately 30 m, imaging primary targets of inland and coastal waters and land. The second satellite targeted for launch in 2027 will be in an ascending afternoon orbit and carry a multi-band, thermal infrared (TIR) imager covering the same primary targets with a 60 m ground sampling distance. The TIR sensor will have a 935 km swath width and a revisit time of about 3 days. The open ocean will be collected by both instruments at 1 km spatial resolution. The SBG observation system is intended to assess inland and coastal aquatic ecosystems, including phytoplankton community composition physiology and change detection in benthic and wetland habitats.

3. Data Products and Algorithms

All three missions have individual working groups, as well as synergistic working groups to identify the range of desired products and applications for each mission (Table 3). This paper is the result of the Aquatic Cross Mission Exchange (ACME) working group whose mission is to identify synergistic opportunities between the three missions including calibration, validation, algorithm developments, uncertainty estimation, data flagging,

Table 2
Comparison of Mission Observational Capabilities

Objectives	Mission comparison:	PACE OCI	GLIMR	SBG
	Science objectives	Global ocean ecosystems; phytoplankton community composition; aerosol and cloud; continue climate data records	Dynamic short-term coastal and ocean processes; seasonal to annual coastal productivity and flux estimates	Fine-scale coastal and inland aquatic and terrestrial ecosystems, hydrology, and geological processes
Temporal	Observation frequency	Once per day	6 per day Gulf of Mexico	VSWIR: ≤16 days[a]
			2 per day or more elsewhere	TIR: ≤3 days[b]
	Resolvable time scales	Weekly to decadal	Sub-diurnal to multi-year	Seasonal to decadal
Spatial	Coverage	Global	Coastal and inland waters of N. & S. America, Caribbean & tropical Pacific	Global land, coastal, island & inland waters. Global ocean at coarser resolution
	Ground sample distance	1.2 km nominal	300 m nadir	VSWIR: 30 m coast/inland
				TIR: 60 m coast/inland
				V-TIR: ~1 km open ocean
Radiometric	Spectral range	UV-NIR: 340–890 nm[c]	UV-NIR: 340–1,040 nm[c]	VSWIR: 380–2,500 nm
		NIR-SWIR: 940, 1,038, 1,250, 1,378, 1,615, 2,130, 2,260 nm		TIR: 3–12 μm multiple bands
	Spectral resolution	UV-NIR: 5 nm	UV-VIS: ≤10 nm	VSWIR: 10 nm
		NIR-SWIR: 45, 75, 30, 15, 75, 50, 75 nm	NIR: 10–20 nm	
	Spectral sampling	UV-NIR: 2.5 nm; 1.25 nm at 640–715 and 740–775 nm (nominal 0.625 nm); NIR-SWIR: discrete	UV-VIS: 5–8 nm	VSWIR: 8–12 nm
			VNIR: 10–15 nm	
	# Bands	>200	~250	VSWIR: >175 VSWIR TIR: > 7
	Signal-to-noise level	UV-VIS: 2,000–3,000[d]	UV: >420 to >650[d]	VNIR: SNR >400 at 500 nm and 1,000 nm[f]
			415–580 nm: >1,000[e]	
		VNIR: 600–1,600[d]	580–720 nm: >500[e]	SWIR: SNR >250 at 1,650 nm and 2,200 nm[f]
			720–1,025 nm: >100 to >750 (40 nm bands)	MIR (3–5 μm): <0.3°K NeDT@750°K, 400–1200°K
		SWIR ocean 1,250 and 1,615 nm bands: 500–1,200[d]		TIR (8–12 μm): <0.2°K NeDT @275°K, 200–500°K
	Number of bits	16	14	14

[a]5–8 days w/CHIME. [b]2 days w/LSTM and TRISHNA. [c]Can reach 320 nm. [d]Top of Atmosphere (TOA) radiance over open ocean for 15 nm aggregated bands. [e]TOA radiance over open ocean for 10 nm aggregated bands. [f]TOA over surface with 25% reflectance.

and data fusion, as well as to provide a common voice to the aquatic science and applications community through joint townhalls and science sessions. ACME will also serve a role in identifying common themes for aquatic research and applications that can be solicited by agencies including NASA, the National Oceanographic and Atmospheric Association (NOAA), and the National Science Foundation.

In addition to atmospherically corrected water-leaving reflectance, the heritage products include chlorophyll-*a* and chlorophyll fluorescence and products that further describe the optical properties of the water column including diffuse light attenuation coefficient, absorption by phytoplankton and colored dissolved organic matter (CDOM), and particulate backscattering.

The aim of these missions is to "go beyond" these heritage products and use the hyperspectral signal to explore new and improved products relevant to the dissolved and particulate matter in the water column, as well as float-

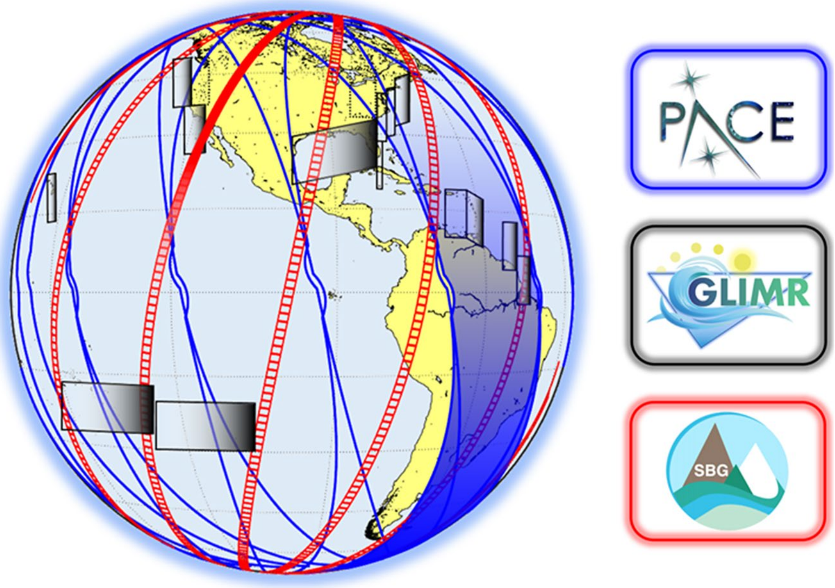

Figure 3. An example schematic showing the swaths of Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) covering the global ocean (blue) at 1.2 km resolution, the narrow Surface Biology and Geology (SBG) swaths covering the coastal regions at 30 m resolution and potentially the open ocean at ∼1 km (red), and the Geostationary Littoral Imaging Radiometer (GLIMR) regions of interest along coastal North and South America, Caribbean (gray polygons), as well as select calibration sites in the open ocean.

ing, submerged, and shallow benthic habitats. As shown in Figure 4, specific regions of the spectrum have applications for different pigments like phycocyanin, which can be produced with sensors that have an orange band at 620 nm (Castagna et al., 2020; Lima et al., 2023). However, we now know that better retrievals for phytoplankton pigments are obtained by using the whole visible spectrum including regions that may not have noticeable or "interesting" features (Kramer et al., 2022). These pigments can be related to the phytoplankton community composition (PCC) through multiple techniques (Cetinić et al., 2023; IOCCG, 2014).

Remote sensing is playing an ever-increasing role in monitoring water quality broadly (Dekker et al., 2018; IOCCG, 2018). Certain parts of the spectrum (Figure 4) are suited for identifying suspended solids, a measure of the clarity or turbidity of the water column (Turner et al., 2022). Moving from the open ocean to more turbid inland waters, new unified approaches are available to better estimate suspended solids, chlorophyll-*a*, and absorption by CDOM across these diverse water types (Pahlevan et al., 2021). More accurate models for estimating light attenuation can be achieved by using the hyperspectral signal (Frouin et al., 2018; Jamet et al., 2012), as well as more advanced inversion models to estimate absorption by CDOM, phytoplankton, and detrital and depigmented particles (Stramski et al., 2019; Twardowski & Tonizzo, 2018). Using the hyperspectral signature will provide new information to better understand the chemical structure of the dissolved organic carbon (DOC) entering nearshore waters from rivers and tidal marshes and its influence on trophic dynamics in estuarine waters (Tzortziou et al., 2008).

In addition, methods have been enumerated to delineate optically shallow water where the benthos can contribute to the signal observed by a satellite (McKinna & Werdell, 2018). With hyperspectral data, characterizing the benthic habitats globally from satellites can also become a reality using a variety of inversion techniques (Garcia et al., 2018; Hedley et al., 2016). The PACE mission is looking to group several water quality products into a single bundle such that beginning and intermediate users can easily access diverse parameters in their region. The bundles will grow as new algorithms come online and can include: chlorophyll-*a*, cyanobacterial indicator, light attenuation at 490 nm, CDOM absorption at 440 nm, net primary productivity, total suspended solids, apparent visible wavelength, and potentially indicators of shallow water and floating algae. Such bundles could prove invaluable and be transferred to the other satellite missions.

Table 3
Aquatic Science Working Groups

Working group name	Missions
Aquatic Cross Mission Exchange (ACME)	PACE, SBG, GLIMR
Aquatic Studies Group	PACE, SBG, GLIMR, International community
GLIMR Science Team	GLIMR
Interagency Chesapeake Bay Working Group	PACE, GLIMR, SBG
IOCCG[a] Ocean Optics & Biogeochemistry Protocols	PACE, SBG, GLIMR, International community
IOCCG Working Groups & Task Forces (Active: Marine Litter, Benthic Reflectance, Atmospheric Correction, Sensor Calibration)	PACE, SBG, GLIMR, International community
PACE Science and Applications Team	PACE
PACE Early Adopters	PACE
PACE Community of Practice	PACE
SBG Algorithms	SBG
SBG Applications	SBG
SBG Calibration and Validation	SBG
SBG Modeling	SBG

[a]IOCCG = International Ocean Color Coordinating Group. www.ioccg.org.

PACE's OCI will be the first global hyperspectral imager with a science and applications team that is tasked with building hyperspectral algorithms to generate new products for public distribution, although initially provisional (Boss & Remer, 2018; Werdell et al., 2019). These products are intended to use the full hyperspectral information to retrieve historic parameters with lower uncertainty or to develop new products ranging from phytoplankton community composition to benthic and floating habitats. The basic algorithms to be produced address aquatic biogeochemistry, biophysics, and biodiversity of floating, submerged, and benthic habitats (Figure 5). Many new algorithms have been developed for use with hyperspectral imagery from PACE at high spectral resolution (<5 nm). While the historic algorithms can be produced from all three missions, porting new algorithms to GLIMR and SBG with lower spectral resolution will require some tuning. In addition, the larger international aquatic optics community will also be contributing novel algorithms across the aquatic domain shown in Figure 5. Not all of the missions will produce all of these products routinely. However, as cloud computing develops further, approaches will be available online to derive products from PACE, GLIMR, and SBG imagery on demand using a suite of different algorithms. For example, Google Earth Engine is a cloud computing platform for processing satellite imagery and other geospatial and observation data that provides online computational power to analyze a variety of satellite imagery. Certainly having global hyperspectral imagery will inspire a new generation of global and locally tuned algorithms for a wide variety of applications.

4. Hyperspectral Field Data

A major challenge for the training and validation of novel societally beneficial products is the scarcity of in situ data spanning the inland to coastal water continuum, an area of great science and applications need. NASA's SeaBASS data archive is an extremely useful repository for numerous types of radiometric, biogeochemical, and biodiversity data and it will be critical for all of the missions to submit in situ data there (Soto Ramos et al., 2020; Werdell et al., 2003). In addition, biodiversity data should also be co-linked to the open-source repository Ocean Biodiversity Information System (OBIS, 2023). Several past NASA-funded interdisciplinary aquatic field campaigns have involved investigations of air-sea fluxes of carbon in the Southern Ocean (SoGasEx), the biology and biogeochemistry of a rapidly changing Arctic Ocean (ICESCAPE), ship-aircraft bio-optical research (SABOR), EXport Processes in the Ocean from Remote Sensing (EXPORTS), and two Earth Venture Airborne missions: the Coral Reef Airborne Laboratory (CORAL) and the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES). The critical need for hyperspectral radiometry data coupled to the many products described

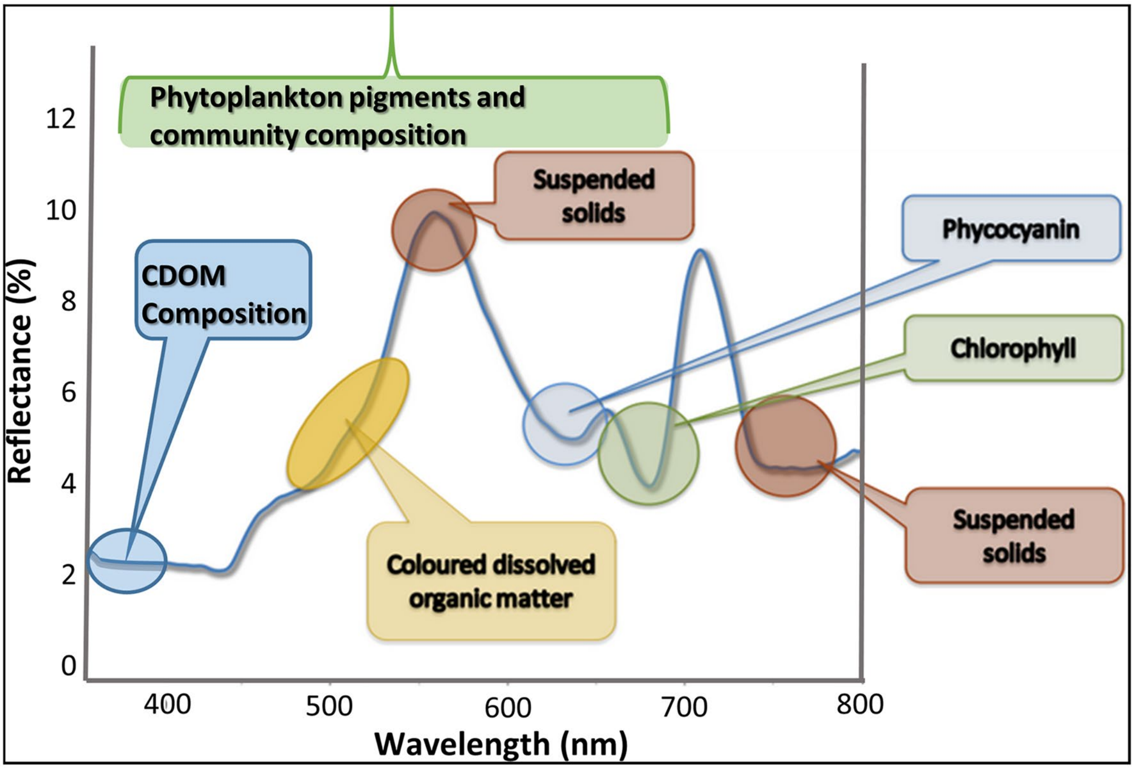

Figure 4. Example spectra from inland water highlight the different parts of the spectrum that are useful for identifying water quality parameters of interest. Many parameters, like phytoplankton pigments and composition, are best retrieved using the whole spectrum. Adapted from Dekker et al. (2018).

in Figure 5 has prompted a host of planned and completed field campaigns to benefit all of the missions. A few of the upcoming NASA sponsored campaigns are outlined below: SHIFT that occurred in 2022, and the upcoming BioSCape and PACE-PAX field campaigns. These campaigns are collectively aimed at reducing risk to the missions and align with Applied Science Focus Areas for PACE, GLIMR, and SBG.

	Aquatic Biogeochemistry	Aquatic Habitat Composition	Aquatic Biophysics
Historic	•Chlorophyll-*a* and Fluorescence Line Height •Particulate Inorganic and Organic Carbon (PIC, POC) •Net primary productivity (NPP) •Suspended Particulate Matter (SPM)	•Optical water types	•Diffuse light attenuation (K_d) •Photosynthetically Available Radiation (PAR) •Absorption due to CDOM and detritus (a_{gd}), phytoplankton (a_{ph}) •Particulate backscattering (b_{bp})
New	*•Phytoplankton carbon* *•Ancillary pigment concentrations* *•Dissolved Organic Carbon (DOC)* *•CDOM Composition* *•Pollutants (oil, plastics)*	*•Floating vegetation composition* *•Benthic composition* *•Phytoplankton community composition* *•Wetland composition*	*•Absorption due to CDOM (a_g) and spectral slope coefficient* *•Absorption due to depigmented (detrital) particles (a_d)* *•Shallow water bathymetry & flooding*

Figure 5. Types of aquatic products that can be produced from hyperspectral imagery on Plankton, Aerosol, Cloud, ocean Ecosystem (PACE), Surface Biology and Geology (SBG), and Geostationary Littoral Imaging Radiometer (GLIMR) either as standard or provisional routine products or within open-source community processors. Hyperspectral capabilities will reduce the uncertainty in many of the historic products, and allow for a host of new products shown in italics.

4.1. SBG High-Frequency Time Series

The SBG High-Frequency Time series (SHIFT) campaign was identified to fill the need for sub-seasonal VSWIR time series data over coastal and vegetated surfaces to conduct representative science value assessments (Cawse-Nicholson et al., 2022). The SHIFT campaign collected weekly airborne hyperspectral observations via the Airborne Visible InfraRed Imaging Spectrometer - Next Generation (AVIRIS-NG) across terrestrial and coastal aquatic environments in Santa Barbara County, California from the end of February through May 2022, paired with field observations for calibration and validation, including radiometry. The study area encompassed the Nature Conservancy's Jack and Laura Dangermond Preserve, the University of Santa Barbara Sedgwick Reserve, parts of the Vandenberg Space Force Base and the Los Padres National Forest, much of the agriculture-dominated Santa Ynez Valley, the Point Conception Marine Reserve Area, the Santa Barbara Channel Long Term Ecological Research sampling sites, and several coastal wetland reserve sites. These regions were selected for their high ecological diversity, rapid phenological change, access to existing field sites with detailed baseline data sets, and proximity to the core team and aircraft base of operations. Overall, the SHIFT campaign provides a critical data set to advance aquatic and terrestrial understanding beyond static or seasonal change to sub-seasonal change at high temporal, spatial, and spectral resolution. Hyperspectral algorithms being tested with data from this campaign include assessing benthic kelp habitats and accuracy of retrievals related to water column biogeochemistry.

4.2. Biodiversity of the Cape

Biodiversity of the Cape (BioSCape) is the first NASA biodiversity field campaign that spans terrestrial to marine ecosystems. It targets South Africa's Greater Cape Floristic Region (GCFR) and includes projects sampling three coastal sites and five inland waters. The GCFR contains two Global Biodiversity Hotspots with the richest temperate flora and the third-highest marine endemism in the world. BioSCape incorporates field observations aligned with airborne imaging spectroscopy from the UV to thermal IR wavelengths (AVIRIS-NG, Portable Remote Imaging Spectrometer (PRISM), and Hyperspectral Thermal Emission Spectrometer and laser altimeter Land, Vegetation, and Ice Sensor aboard the NASA G-III and G-V aircraft. BioSCape precursor data for future missions includes phytoplankton and floating aquatic biodiversity and water quality. These data collections will enable algorithm testing and processing workflows for maturation and validation of new hyperspectral algorithms for phytoplankton pigments, community composition, carbon, and net primary productivity in the GCFR, including inland waters and major upwelling regions of the world ocean.

4.3. PACE-PAX

PACE will support a validation team to provide global and regional data for OCI, HARP2, and SPEXone performance assessments after launch. In addition, PACE has planned an airborne field campaign, the PACE Postlaunch Airborne eXperiment (PACE-PAX; https://espo.nasa.gov/pace-pax), to obtain coupled hyperspectral radiometry, multi-angle multi- and hyperspectral polarimetry, and LIDAR measurements, as well as airborne in situ measurements. Two aircraft will be deployed (CIRPAS, NASA ER-2) off the California coast scheduled from 3 to 27 September 2024. A suite of 11 different instruments for spectrometry, polarimetry, and ancillary atmospheric measurements have been identified for the airborne mission. Of note, the hyperspectral imaging spectrometers PRISM and PICARD will be flown, as well as airborne versions of HARP2 and SPEXone. The main goal of PACE-PAX is to provide performance assessments and proxy measurements that can only be performed with an airborne, multi-sensor field campaign. These measurements will help evaluate uncertainties associated with atmospheric correction with complex atmospheres and retrieval of climate-quality water-leaving reflectance. Associated aquatic field campaigns from ships-of-opportunity are proposed to evaluate hyperspectral algorithms related to coastal and open ocean phytoplankton and biogeochemical properties.

5. Calibration and Validation

Historically, aquatic remote sensing instruments require a robust prelaunch characterization and on-orbit calibration monitoring (McClain et al., 2022). For prelaunch calibration, it is recommended to use similar testing methods and references to maintain consistency across all three missions (Turpie et al., 2023). We can also rely on common references once the instruments are on-orbit to intercompare for consistency. Aquatic remote sensing has historically used observations of irradiant flux from the Sun and the Moon as references, the Moon being theoretically an ideal common reference (Stone et al., 2020).

A common solar irradiance reference data set should be used across all three observatories to maintain consistency in solar calibration and reflectance data products. This value is used to derive downwelling spectral irradiance under clear sky conditions at Earth's surface and used to produce estimates of water-leaving reflectance from space-based measurements and also used for solar calibration on orbit. Hence, a common standard needs to be used across all past and future missions to avoid biases. The current recommended data set accepted by the Global Space-based Inter-Calibration System (GSICS) as an international standard (Stone et al., 2021) is the Total Solar Irradiance Sensor (TSIS)-1 Hybrid Solar Reference Spectrum (Coddington et al., 2021, 2023).

Using the Moon as a full-system measure of radiometric responsivity changes on-orbit (Lunar calibration) has been a largely successful activity for the past quarter-century despite many challenges. These challenges are rapidly being addressed by various efforts, including the current airborne Lunar Spectral Irradiance mission (Woodward et al., 2022). Such improvements will provide a more consistent, stable sub-percent absolute calibration on orbit, improved trending capability, and a common reference for satellite constellations (Kieffer, 2022; Stone et al., 2020).

PACE's OCI was designed to maintain the high-quality ocean color climate data records (Mélin et al., 2017). OCI is being calibrated with the Goddard Laser for Absolute Measurement of Radiance, which provides absolute radiometric calibration to better than 0.5% accuracy. Extensive on-orbit calibration and performance assessment activities will be conducted during each mission's 60-day to 90-day commissioning period to establish a baseline of radiometric gain factors, performance, and spectral calibration before the commencement of formal science operations. The on-orbit radiometric calibration equation for PACE's OCI (Meister et al., 2019) is based on over 25 years of ocean color satellite sensor heritage and will also be used for GLIMR. Relative gain factors will be recorded as a function of time and trended on-orbit with solar diffuser and lunar measurements. All relevant calibration data are expected to be made publicly available online following NASA's Earth Data and Information Policy (ESDS, 2023). SBG will have heritage calibration using land targets and the dark side of Earth pioneered with the EMIT imaging spectrometer on the space station (Green et al., 2023).

One of the advantages of having three hyperspectral imagers on orbit at the same time is the ability to inter-compare the missions using the Earth's surface for inter-calibration or inter-validation (Turpie et al., 2023). As shown in Figure 3, however, the swaths of PACE and SBG are quite different and it will take time once on orbit to build a data set of coincident clear sky pixels with homogenous conditions over a 1.2 km scale (the OCI cross-track center pixel size at its 20° tilt) for inter-comparison. None of the coincident observations between PACE and SBG share common viewing geometry. Therefore, at-sensor radiometric calibration inter-comparison is not possible. Therefore, only surface data products can be intercompared (Turpie et al., 2023). There will likely be opportunities to observe near-simultaneous, like-geometry observations between GLIMR and the other two missions, especially where observations are collected frequently, such as over the Gulf of Mexico. In this way, GLIMR might serve to transfer the calibration scale from PACE to SBG.

Ocean color remote sensing has also historically required system vicarious calibration (SVC) to remove inherit biases in the atmospheric correction and residual biases in the radiometric calibration. SVC uses high-quality and national reference laboratory traceable radiometric measurements made at selected aquatic sites with very well-constrained atmospheric conditions and generally clear water with low spatial and temporal variability (NRC, 2011; Zibordi et al., 2015). These sites have been maintained nationally and internationally for the benefit of all ocean color missions. Of note, MOBY (https://mlml.sjsu.edu/moby/) moored off the island of Lanai, HI, USA, is a radiometry resource used for SVC of ocean color sensors since the launch of NASA's SeaWiFS that has been in continuous operation since 1997 (Voss et al., 2017). For the suite of new hyperspectral satellites, similar moored platforms in historic and new locations and different platforms like profiling systems are being considered, all equipped with high-quality hyperspectral radiometric instruments (Antoine et al., 2020; Barnard et al., 2022; Liberti et al., 2020). All SVC data sources are expected to be made available to PACE, GLIMR, and SBG, as well as the international community at-large.

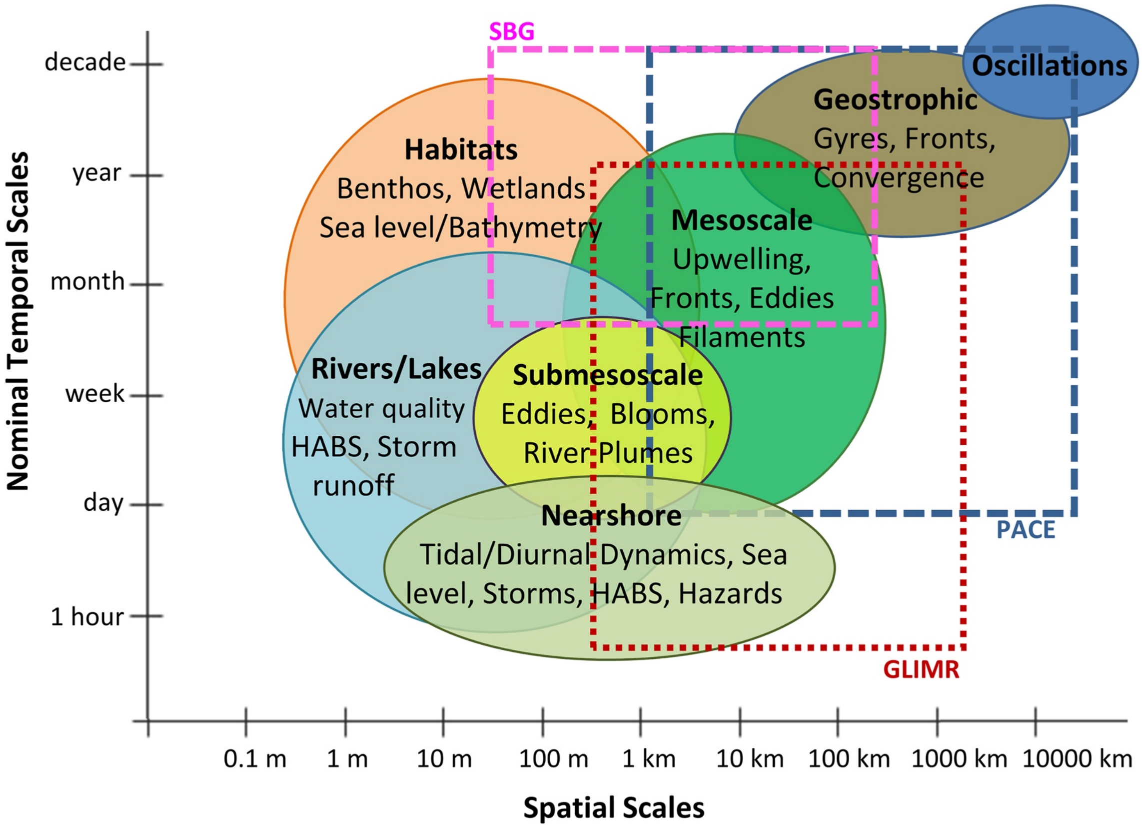

Figure 6. Spatial and temporal domains for each mission and example aquatic processes that can be sampled at different time and space scales. Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) and Surface Biology and Geology (SBG) are global missions (dashed) and Geostationary Littoral Imaging Radiometer (GLIMR) is regional (dotted). Nominal temporal scale is shown that does not consider cloud cover. HABS (Harmful Algal Blooms), Oscillations refer to large basin-wide climate patterns such as El Niño-Southern Oscillation. Following from Dickey et al. (2006) and Hedley et al. (2018).

6. Advancing Aquatic Science

Each mission provides unique measurement attributes that advance knowledge in different aquatic processes spanning space and time (Figure 6). These trends vary from decadal large-scale oscillations across the major ocean basins such as El Niño-Southern Ocean Oscillation, Pacific Decadal Oscillation, and North Atlantic Oscillation to the diurnal and tidal nearshore processes that shape fine-scale communities and features along the coastline. A major advantage of hyperspectral sensing is the ability to better characterize size distribution and phytoplankton community composition from open ocean ecosystems to benthic (seafloor) and wetland ecosystems and the responses of these communities to environmental forcing. These three missions will also provide observations from space to help understand how climate change will impact faraway places like the Southern Ocean, as well as regional coastal communities. For example, rising sea level has worldwide consequences because of its potential to alter coastal ecosystems by increasing the prevalence of recurrent tidal flooding events and intensifying storm surge events. Satellite imagery across different spatial and temporal domains from these three missions will be important for assessing climate change and its impacts on aquatic ecosystems broadly. Some of the key aquatic science to be addressed from each mission are outlined below.

PACE's 1-day to 2-day global coverage, wide swath, high sensitivity, and spectral measurement capability will enable quantification of aquatic processes at decadal, interannual, seasonal to daily scales across the global ocean including the major gyres and mesoscale and submesoscale eddies (Figure 6). In the open ocean, for example, nutrients for phytoplankton growth are largely provided by upwelling events that bring nutrients from deep waters up to the surface layer. Recent results show how phytoplankton can respond both in terms of growth and physiological status to nutrients provided through the deposition of desert dust carried through the atmosphere as aerosols (Westberry et al., 2023). Missions like PACE with hyperspectral capabilities coupled to polarimetry will be well suited to further assess the relationship between dust aerosols and phytoplankton community composition and biogeochemical dynamics. Furthermore, mesoscale eddies on the order of 100 km are mainly generated along the continental coasts and south of the main archipelagos and occupy ∼25% of the ocean's surface area at any given time (Chaigneau et al., 2009). Eddies can influence phytoplankton dynamics and biogeochemical cycling through a variety of mechanisms, including advection of nutrients, ecosystems, and upper ocean mixing, and typically result in chlorophyll-a anomalies based on the direction of flow (Gaube et al., 2014). However, less information is known about the shifts in phytoplankton community structure in response to eddies due to the challenges in sampling such events from ships (Brown et al., 2008). Hyperspectral sensing from PACE will help shed light on potential successional transitions from photosynthetic bacteria to diatoms in response to mesoscale eddies and the underlying mechanisms.

Climatologically, shifts between El Niño, La Niña, and neutral conditions in Pacific Ocean sea surface temperatures and associated global-scale oceanographic and meteorological patterns also result in widespread changes in phytoplankton community composition, biomass, and productivity (Racault et al., 2017; Schollaert Uz et al., 2017). For instance, intense upwelling along the equatorial Pacific and off-the-coast of central South America supports high phytoplankton biomass and productivity dominated by diatoms during neutral conditions, and weakening of upwelling to warm stable sea surface waters as the Pacific transitions to El Niño conditions engenders a change in phytoplankton phenology, community composition and reduces productivity and biomass (d'Ortenzio et al., 2012; Sharma et al., 2019). PACE will observe such vast changes in phytoplankton across the Pacific Ocean during transitions between El Niño, La Niña and neutral conditions at the relevant spatial coverage from tens to thousands of kilometers and timescales from weekly to seasonal and interannual. Having near-daily global hyperspectral imagery from PACE will allow us to observe the interplay not just of phytoplankton "biomass" estimated from chlorophyll-*a*, but of phytoplankton communities (Chase et al., 2022) leading to new understanding of biological-physical coupling and trophic dynamics across the vast coastal and open ocean.

GLIMR's observation frequency (∼hourly to three times per day), sensitivity, and spectral capability make it well-suited to quantify nearshore processes along the US coast (Figure 6), including the mass export of sediments, particulate organic carbon (POC), and DOC from river mouths to outer areas of coastal ocean waters. High precipitation events from tropical and other storms occur with some regular frequency along the US East and Gulf of Mexico coastal states prompting the export of vast amounts of sediments, organic matter, and nutrients through rivers into estuaries and across the coastal ocean. Flood waters flowing across and through landscapes swell rivers with fast-flowing waters and impart high concentrations of particles and dissolved constituents. This hydrological response is rapid, occurring on the order of tens of hours to several days, and exports significant amounts of freshwater and matter into marine waters (Chen et al., 2020). Even during such extreme events, tidal cycles and wind shear modulate the flux of freshwater and constituents into estuaries and across the coastal ocean.

The high-frequency variation in hydrodynamic circulation and sediment dynamics on the scale of a few hours, as well as the ephemeral aspect of tidal flood water outflow from the coast of approximately less than 1 week, requires a sensor with GLIMR's measurement attributes and scheduling flexibility. Surface currents from temporally evolving water-leaving ocean reflectance from GLIMR can be determined through techniques such as maximum correlation analysis (Warren et al., 2016; Yang et al., 2014). Artificial neural network approaches can extend GLIMR's surface layer concentrations of suspended sediments, POC and DOC throughout the water column, along with GLIMR-derived surface currents combined with hydrodynamic model output of lower water column density and velocity fields to compute mass fluxes (Mannino et al., 2016; Signorini et al., 2019). Following this or similar methodology, GLIMR will reduce the current uncertainties in the mass flux estimates of sediments, POC, and DOC with its observations at relevant temporal scales (Signorini et al., 2019).

SBG's comparatively high-spatial and hyperspectral observations are well suited to map spatial extent and quantify the biomass and production of inland and coastal habitats globally on seasonal to interannual timescales. Covering the world's Exclusive Economic Zones and Marine Protected Areas, Figure 7 highlights the inland, coastal, and island regions that will be sampled by SBG at 30-m resolution with a nominal 16-day revisit time. Submerged aquatic vegetation (SAVs), for example, are an important habitat that can be better monitored with SBG measurements. Found in freshwater, estuarine, and marine ecosystems, SAVs provide critical ecosystem services such as habitat for fish and other aquatic organisms, nutrient remediation, food for aquatic organisms and humans, erosion mitigation, and carbon storage and sequestration (Hestir et al., 2016). SAVs include several groups of vascular plants (seagrasses, pondweed, water milfoil) and macroalgae (red, brown, and green). Of

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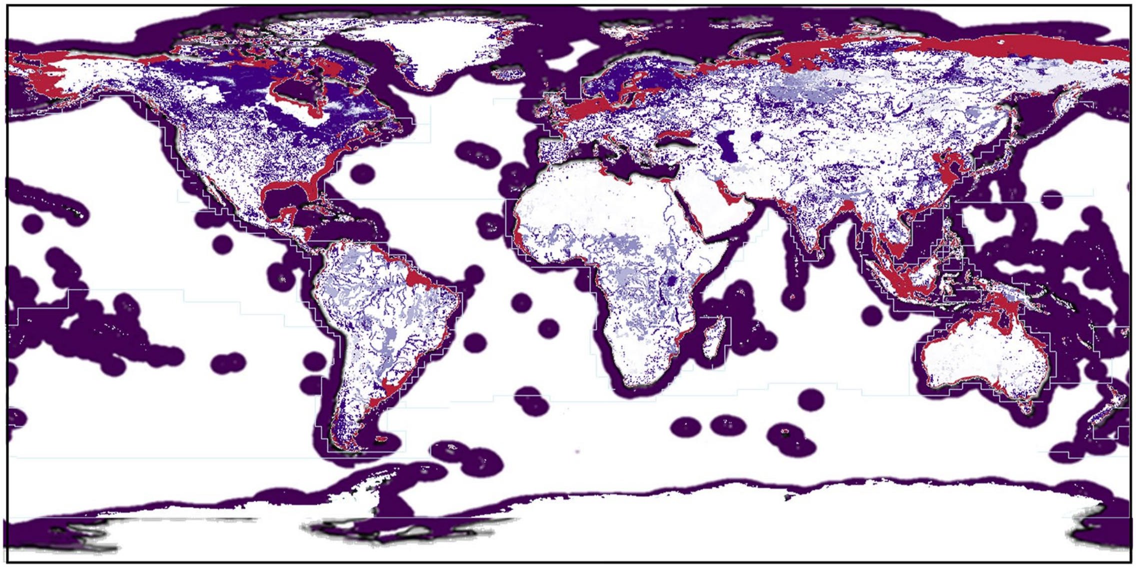

Figure 7. Global distribution of coastal and inland aquatic ecosystems. Purple colors on land represent the concentration of inland wetlands, lakes, rivers, and other aquatic systems shaded light to dark to represent greater percentage of areal coverage (UNEP-WCMC, 2005). Red indicates regions where water depth is less than 50 m and where land elevation is less than 50 m. Dark violet represents the coastal regions to be sampled at 30-m spatial resolution by the SBG mission.

concern, seagrass meadows are declining in many regions worldwide as a result of coastal development, nutrient loading that reduces light availability, climate change, and cascading impacts of fishing (Orth et al., 2006; Sudo et al., 2021). In addition, the natural forces underlying the distribution and variability of seagrass distributions (e.g., nutrient limitation, storms, and disease) have not been well documented. Regular monitoring of seagrass cover and ecosystem structure, and better mapping of existing seagrass extent, is critical to modeling and managing coastal and reef fishery production, the global carbon cycle, and tracking impacts of climate change and coastal eutrophication (Duffy et al., 2019).

Methods for remote sensing seagrass habitats have evolved over the last 50 years (Kutser et al., 2020), as well as the satellite technology to assess changes in optically shallow water across space and time (Dierssen et al., 2021; Giardino et al., 2019). With hyperspectral resolution, SBG will be better able to differentiate green seagrass from other green benthic constituents such as benthic microalgae and macroalgae (Garcia et al., 2020). Due to the patchy spatial distributions of seagrass meadows, such mapping and monitoring of seagrass (and many other SAVs) requires a very high spatial resolution capability ideally <5–10 m, while 15–30 m resolution provides sufficient capability. For example, Hill et al. (2014) found that coarsening the spatial resolution of imagery from 1 to 10 m decreased retrieval of biomass for SAV by about 10%, but further coarsening up to 60 m pixels did not produce any further change in retrieval bias (Hill et al., 2014). Hence, SBG will have sufficient spatial resolution (30 m) and revisit capabilities (16-day) to resolve seasonal and interannual changes in shallow benthic aquatic ecosystems across the globe.

7. Linking Processes Across the Aquatic Continuum

Many synergies will exist between these missions, but a primary linkage will be to track the water cycle and the transfer of materials from inland lakes all the way to open ocean ecosystems. Biogeochemical transformations occur continuously, albeit at different rates, across aquatic networks and salinity gradients (Ward et al., 2020). Freshwater plumes, watershed runoff, and tidal wetland flushing have a vast influence on carbon and nutrients dynamics in estuarine environments, shaping coastal ecosystem ecological functions and metabolic balance (Tzortziou et al., 2008). As a parcel of water departs a terrestrial watershed and interacts with the coastal ocean, a suite of biological and physical changes occur over short time and space scales. The type of environments encountered from the transition to open ocean waters will influence the evolution and transport of these materials, as they are modified by local biogeochemical processes and interactions with diverse coastal ecosystems (e.g., estuaries, salt marshes, mangrove forests, and seagrasses). Within the context of coastal water masses, the most

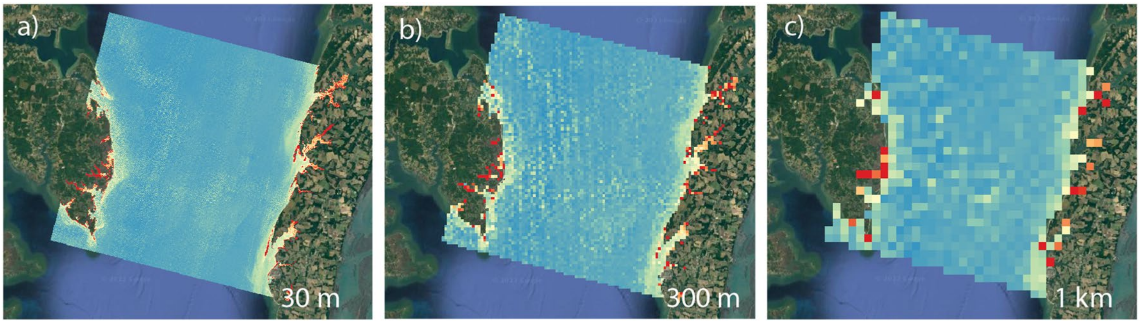

Figure 8. PRISMA-derived (30 m) chlorophyll-*a* in the Chesapeake Bay that was spatially resampled to (a) SBG VSWIR (30 m), (b) GLIMR (300 m), and (c) PACE (1 km) resolutions to highlight the spatial capabilities of each mission within coastal environments. Imaging of fine scale features is enabled with SBG VIS-SWIR, but on sub-monthly timescales. Diurnal to daily feature variations will be possible with GLIMR and PACE, albeit at slightly coarser resolutions. Combination of data from all three missions will enable a full spatial and temporal view of features and their change within coastal environments.

fundamental and persistent of environmental cycles—the daily cycle of sunlight—elicits a multitude of phytoplankton photo-physiological responses within the water column over the course of a day that may affect the total rate of ocean carbon fixation.

These processes collectively impact the production and biodiversity of the plankton community, as well as inventories of carbon and nutrients and export production to the deep sea and seabed, which influence the sequestration of atmospheric carbon dioxide. Furthermore, physical influences in the near-shore environment due to freshening, tidal mixing, wind-driven resuspension, and transport can impact net production and subsequent fluxes across coastal ecosystems. For example, fluvial discharge can introduce significant fractions of suspended sediment, organic carbon, and nutrients, simultaneously providing nutrients that were previously limited, while also limiting light needed for growth. Depending on the dominance of the processes (i.e., increasing nutrient availability vs. increasing light limitation), the local aquatic ecosystem may shift from net autotrophic to net heterotrophic, or vice versa (Najjar et al., 2018).

Understanding such processes requires new satellite imagery that captures a large range in time and space scales associated with dynamic inland and coastal ecosystems and large-scale open ocean ecosystems. A recent review of water quality remote sensing highlighted that wider rivers, lakes, reservoirs, estuaries, and coastal marine waters could be adequately resolved by current or planned future satellite remote sensing technology (IOCCG, 2018). Of the 117 million lakes on Earth, however, very few are monitored regularly or systematically from space, and often only at regional or continental scales (Dörnhöfer & Oppelt, 2016; Seegers et al., 2021). Land-sea sub-mesoscale processes, tidal inflections, responses to rapidly varying winds, turbulence, coastal currents, and nutrient mixing can all impact the distribution, fate, and export of dissolved and particulate organic carbon. Presently, we are unable to quantify such processes at the resolutions of our current ocean color constellation (Muller-Karger et al., 2018) and lack sufficient in situ networks to sufficiently monitor these resources on which the majority of human populations depend. Indeed, the requirements for the comprehensive monitoring of these ecosystems are nearly as diverse as the processes being resolved, but recent technological advances have enabled us to start moving beyond studying the end-effects of various processes, and instead into the study of the processes themselves. Importantly, we require the ability to resolve the diurnal evolution of carbon stocks through multiple observations, the changes to the stocks over the course of time, and their spatial dynamics. Instead of parameterizing, or modeling the time-varying component from weekly to monthly imagery, the actual observation of these processes at their natural time and space scales (e.g., phytoplankton growth rates) is poised to revolutionize how we study the Earth system (Sosik et al., 2003).

The unique hyperspectral capabilities of SBG, GLIMR, and PACE will move beyond observing biogeochemical gradients and improve the characterization of changes in carbon quality and fluxes across spatial scales (Figure 8) through a holistic and integrated approach coupled with advanced modeling techniques (IOCCG, 2020). With a focus on terrestrial, inland, and coastal systems, the high spatial resolution imagery from SBG will be well-suited for characterizing the influence of land-based processes, aquatic benthic and floating habitats, and biogeochemical exchanges across terrestrial-aquatic interfaces (Singh & Townsend, 2023). From a geostationary orbit, GLIMR provides the temporal dimension needed to track transient events and quantify biological and biogeochemical rates, including primary production, microbial transformations, and marine photochemical carbon mineralization. With global coverage at 1–2 days revisit, and a combination of ocean color and polarimetric measurements, PACE will provide novel insight into the changing role of Earth's ocean as a carbon source or sink at the global scale. Cross-mission synergies will uniquely link biogeochemical processes across different aquascapes and spatiotemporal scales, connecting inland and coastal ecosystem biogeochemical functioning to ocean food webs, large-scale climate variability, and global environmental issues.

8. Cross-Cutting Societal Applications

A recent analysis found that over 50% of the world's population lives within 3 km of a surface freshwater body (Kummu et al., 2011). Moreover, 10% of the world's population live in low-lying coastal regions where rising sea levels will increase the risk of floods and urban disasters (McGranahan et al., 2012). There is a growing need to make remote sensing products and applications to assess, respond, and potentially mitigate the impact of humanity on aquatic environments and the impact of a changing aquatic environment on humanity. Applied science is the use of scientific knowledge to advance society in support of stakeholder needs and to optimize decision-making processes (Scott & Urquhart, 2020). All three of these NASA missions have begun to engage a broad range of stakeholders and nontraditional users through proof-of-concept studies and applied research that may lead to operational applications. The importance of engaging stakeholders before launch to prepare the community to extract maximum societal benefit from new space-based observations was established with the NASA Soil Moisture Active Passive (SMAP) mission (Brown & Escobar, 2013). NASA has continued to engage potential applied users of its satellite data with the ocean color and aquatic communities (Culver et al., 2021; Lee et al., 2022; Schollaert Uz et al., 2019; Scott & Urquhart, 2020). These activities include listening to operational practitioners to understand needs that satellite observations could help address and iterating with these practitioners on potential solutions through a user-centered design process. Broader societal use and benefit from Earth observations by a great number of sectors, beyond the academic and federal partners, may require value-added service providers or boundary-spanning organizations who can tailor products to specific stakeholders' needs and workflows. In addition to the new science possible through the combination of these three missions, the application of this science to solving societal challenges will improve current capabilities and unlock new potential. Selected examples are included here to illustrate the diversity of applications being developed.

8.1. Harmful Algal Bloom Detection and Monitoring

Aquatic ecosystems provide critical services that support humankind and are increasingly pressured by population growth and changing climate. These pressures are altering phytoplankton growth rates, species composition, and land-to-ocean fluxes that impact biodiversity, affect global biogeochemical cycles, and invoke feedbacks in the climate system. Such impacts, in turn, give rise to more frequent and expansive harmful algal blooms (HABs) that are detrimental to tourism, fisheries, and human health. Certain phytoplankton groups, including cyanobacteria, dinoflagellates, and diatoms, can pose a significant threat to the environment, human, and animal health through recreational and drinking water exposure (IOCCG, 2014). Different phytoplankton taxonomic groups contain different suites of pigments for absorbing visible light (Smith & Bernard, 2020). In addition to optical measurements of chlorophyll and remote sensing reflectance in surface waters, leveraging the combination of hyperspectral ocean observations from PACE, GLIMR, and SBG will allow us to understand phytoplankton community composition (PCC), differentiate between phytoplankton groups, and identify taxonomic groups commonly associated with harmful algal blooms. Hyperspectral measurements from PACE, SBG, and GLIMR can be used to develop algorithms that retrieve phytoplankton groups based on reflectance signatures and associated accessory pigments in inland, estuarine, and coastal waters.

Comprehensive valuation studies in this sector are scarce but estimated to be significant. For example, in 2014, a 2-day ban was issued on drinking and cooking with tap water for more than 400,000 residents due to a toxic algal bloom in western Lake Erie that exceeded guidelines for safe drinking water. The economic impact of that bloom alone was estimated at $65 million (NOAA GLERL, 2014). A study by the NASA VALUABLES consortium for a 2017 HAB event on Lake Utah determined that an earlier warning of cyanobacteria from satellite data in combination with in situ sampling reduced illnesses and avoided approximately $370,000 in health care, lost work, and other costs from this single incident (Stroming et al., 2020). Case studies have also shown negative impacts on local property values from harmful blooms (Ritzman et al., 2018).

Multi-mission data synergies between these three missions will enable assessment of HABs within inland and coastal systems of varying size including small (>30m) inland rivers and lakes with SBG, narrow estuarine tributaries (>300m) with GLIMR, to mainstem estuary and open coastal systems (>1 km) with PACE. Similarly, the temporal coverage of GLIMR (3–6 observations/day), PACE's OCI (daily), and SBG VSWIR (16 days) addresses varying time-related research and application challenges. GLIMR will enable dynamic assessment of harmful algal blooms including the sub-diurnal formation, development, and trajectory of blooms, and PACE will enable measurements of daily (depending on cloud cover) variability critical for tracking HAB prediction and forecasting.

The combination of high temporal, spectral, and spatial measurements from GLIMR, PACE, and SBG will provide HAB water quality managers with critical information for integrated coastal assessment for early response, containment, and timely advisories. Additional products relevant to HAB applications will include species-specific HAB detection indices (*Karenia brevis* and *Microcystin* spp.) and a floating algae biomass product from GLIMR, SBG TIR temperature products, and PCC, fluorescent line height (FLH), amongst others from PACE and GLIMR.

8.2. Oil Spill Identification and Management

Identifying and responding to oil spills is a complex challenge that can be addressed through a synergistic combination of measurements from multiple Earth observation missions. Merging data from the PACE, SBG, and GLIMR missions will support better disaster mitigation, management, and decision outcomes compared to data from one mission alone. Hyperspectral measurements enable the detection of the unique spectral features that are diagnostic of oil in and on the ocean surface. Current efforts to use hyperspectral imagery for this have been largely opportunistic via airborne deployments in response to major spills (Hu et al., 2018). Continuous hyperspectral measurements will facilitate the development of algorithms that can operationally differentiate between varying components in the water and characteristics of oil and oil thickness. PACE OCI and SBG VSWIR will include bands in the SWIR which will be crucial for identifying oil slicks, spectrally differentiating between various types of oil slicks (crude oil vs. emulsified oil), and quantifying oil thickness in the ocean (volume). With its daily global revisit and high signal-to-noise (SNR), PACE will have the ability to capture most large (>1 km^2) oil spill events. PACE polarimetric data can also be used to derive ocean surface refractive index for every sun-glint-contaminated pixel that can potentially be related to oil type and thickness (Ottaviani et al., 2012, 2019).

Configurable to respond to episodic events and disasters, including oil spills, GLIMR will have the capability to pause its primary sampling pattern in order to observe events of national importance. Frequent (potentially sub-hourly in disaster event mode) observations from GLIMR will enable the emergency response manager's access to the spatio-temporal history and residence time of a spill and will provide data for trajectory analyses. The SBG VSWIR sensor will significantly improve assessments and coastal oil spill mitigation by enabling the detection of small oil spills/slicks, spill irregularities, ship track spills, and/or underwater oil seeps in near-shore and inland waters (30 m ground sample distance).

8.3. Carbon Monitoring, Reporting, Verification

Carbon management—including monitoring, reporting and verification—has become the focus of many different sectors of society, including the private sector, as well as local, state, and federal government agencies. Consistent and repeatable monitoring will be required as humanity transitions toward a carbon neutral future. Optical and thermal remote sensing provides an independent and objective top-down approach for monitoring terrestrial and aquatic carbon stocks and fluxes on global and regional scales. Moreover, satellite-based remote sensing can significantly reduce the cost of verification of carbon emissions and storage, allowing carbon programs to scale up as well as increase transparency in and access to carbon markets.

A key science question that PACE, GLIMR, and SBG are well-positioned to answer, is "What are the fluxes of carbon between and within ecosystems, and how and why are they changing?" The similar hyperspectral capabilities of the three missions will uniquely allow the development of a suite of common satellite data products from land-use/land-cover change characterization to aquatic dissolved and particulate organic and inorganic carbon concentrations at multiple spatial and temporal scales that can be readily incorporated into policy-based carbon management systems. Integration of multi-mission data products with deep learning algorithms will aim to inform model estimates of carbon dioxide removal and sequestration across a range of ecosystems, from blue carbon habitats (e.g., salt marshes, seagrasses, and mangroves) to open ocean environments, across different climate change scenarios. Merging satellite imagery from different missions will provide a unique opportunity to monitor carbon sources, sinks, and fluxes between ecosystems, over different spatial scales (from 10 m to 1 km) and across the continuum of terrestrial, inland, coastal, and open ocean waters, locally, regionally, and globally. This is essential for the development of common and interoperable carbon monitoring data products, standards, and sharing systems, in support of local, state, national, and international carbon monitoring, reporting, and verification initiatives. Moreover, the focus of SBG, GLIMR, and PACE on identifying core established products and algorithms characterized by low uncertainty is key toward meeting the levels of precision and accuracy required by carbon trading activities.

9. Fusion, Assimilation, and Beyond

Measurements from these three upcoming NASA sensors will not occur in isolation, but will be most valuable when linked together with existing and future satellite sensors and algorithms from across the international community. Techniques for handling the "big data" involved with merging satellite imagery, particularly hyperspectral imagery, are underway to merge and evaluate data sets automatically in the cloud (Dierssen et al., 2021; Gorelick et al., 2017). In the context of assessing aquatic processes, fusion of high spatial resolution optical satellite imagery and synthetic aperture radar data, for example, has been shown to be particularly effective at mapping tidal marshes, functional vegetation classes, and inundation extent (Lamb et al., 2021) providing new insight into how hydrological forcing shapes variability in biogeochemical exchanges across the wetland-ocean continuum. Imagery at multiple scales over a deltaic marsh-estuary system in the northern Gulf of Mexico captured long-term trends in DOC in response to landscape change driven by both geological and man-made processes (Liu et al., 2019). Data fusion of 10–300 m imagery illustrated the impact of freshwater plumes, extreme events, tidal marsh outwelling, and estuarine biological activity on biogeochemical gradients in urban estuaries and their margins (Cao & Tzortziou, 2021; Ward et al., 2020). These case studies show the power that will be harnessed by merging imagery across time and space scales. More can be done to develop algorithms that link spectrometry with data from hyperspectral and hyperangular polarimeters, altimeters, lidars, and scatterometers to better understand phytoplankton community response to environmental forcing on time scales of weeks to months (Gaube et al., 2014).

In addition, the assimilation of ocean color imagery into three-dimensional biogeochemical and ecosystem computer models provides a rigorous method to combine observations and models into a unified coherent narrative. Assimilating satellite imagery into regional and global models will provide a broader context to fill in gaps when imagery is not available and to provide regional forecasts of environmental conditions. As noted in a recent review of the synergies between ocean color data and models (IOCCG, 2020), biogeochemical modeling continues to advance with the inclusion of additional nutrients and carbon pools and the ability to resolve more diversity including mixotrophs, bacteria, viruses, and other trophic levels. Having additional spatial and temporal imagery and expanded biodiversity information from these new NASA hyperspectral regional and global missions should help reduce uncertainties in these models and improve predictive skills. This highlights how remote sensing and modeling communities need to work closely together to align the products and their associated uncertainties with modeling needs.

From headwater streams to marine waters, aquatic ecosystems are intricately linked. The ocean is connected to the land both via atmospheric transport of urban pollution as well as via riverine and groundwater discharge (Moore, 2010). However, the transfer of materials goes both ways from storms impacting the coastline and depositing materials inland to large mats of the pelagic macroalgae *Sargassum* washing up into harbors and beaches (Wang & Hu, 2021). No vantage point can capture a synoptic view of the aquatic connectivity better than Earth observations from space. New technology afforded by PACE, GLIMR, and SBG missions will expose new ways to observe and monitor the regional and global aquascapes and the continuously changing dynamics of our environment. Imaging spectroscopy is an important doorway leading to even more new technology, such as satellite-based lidars, that will allow us to observe the water column. As Rumi once said, "the door is wide and open."

Data Availability Statement

This is an overview paper with no data sets used. The paper notes that NASA will make all data and imagery related to these three missions open access and findable, accessible, interoperable, and reusable (FAIR).

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